Radioactive Waste Storage in the Arid Zone

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BY THE TURN of the century, nuclear power may generate more than one-half of the electric energy, and about one-third of the total energy consumed in the United States [*Thompson*, 1971; *Chapman et al.*, 1972]. By 2020, the total quantity of high-level radioactive wastes (HLW) generated as a by-product of nuclear fuel reprocessing for such power generation may total about 900,000 m^3 as liquid or 70,000 m^3 as solid [*Gera and Jacobs*, 1972]; the radioactivity of long-lived nuclides in the HLW will total about 8.7×10^{10} Ci [*Gera and Jacobs*, 1972]. (High-level wastes are defined as wastes containing at least 1 Ci of radioactivity per liter of liquid, or 70 Ci/kg of solid [American Institute of Chemical Engineering, ANSI Standard N5.8-1967]. Wastes from chemical processing of irradiated nuclear fuels typically contain several hundred to several thousand curies per gallon [*Fox*, 1969].)

Present U.S. Atomic Energy Commission policy [*Federal Register*, 1970] on disposal of these wastes includes the following steps: interim storage as liquid; conversion to solid; interim storage as solid; transportation to, and storage or disposal in, a federally operated surface or subsurface repository. Storage or disposal must prevent contact of the nuclides with atmosphere, biosphere, or hydrosphere for periods of at least one thousand to several hundred thousand years. ^{90}Sr and ^{137}Cs, which make up 99% of the projected curie accumulation at year 2020 [*Gera and Jacobs*, 1972], have relatively short half-lives of 28–30 years and decay to safe levels within about 1000 years. The longer containment times are needed to permit decay to safe levels of the long-lived transuranic radioelements, namely, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Am, and ^{243}Am, with half-lives ranging from about 85 to 24,000 years.

(If the toxic radioactive daughters of the listed transuranic elements are also considered, specifically the daughter ^{237}Np, containment times of millions of years may be required [*Isaacson and Brownell*, 1973]. However, the total curie content of these daughters after 500,000 years is only about 10^{-5} that of the transuranic parents in the reprocessed waste [Eric Meyer, personal communication, 1974]; accordingly, maximum containment times of 500,000 years only will be considered here.)

The term 'storage,' as used in the radioactive waste literature, implies that the waste can be retrieved should such a step be intended or become necessary. In contrast, the term 'disposal' implies placement without future intent or possibility of retrieval. The term 'ultimate disposal' is used by some workers to refer to two specific modes of HLW handling, specifically, the shooting of such wastes into space or their transmutation to short-lived radioactive nuclei by means of bombardment with neutrons. An excellent recent review of the contrasting philosophies of radioactive waste disposal is given by *Kubo and Rose* [1973].

Numerous methods for the storage or disposal of HLW have been proposed in the last two decades, e.g., storage or disposal on or beneath continental areas [*National Academy of Sciences–National Research Council*, 1957, 1966]; disposal in the ocean bottoms, including subduction zones [*Slansky and Buckham*, 1969; *Bostrom and Sherif*, 1970; *Francis*, 1971; *Silver*, 1972]; ultimate disposal by shooting the wastes into space [*Slansky and

Buckham, 1969; *Platt and Ramsey*, 1973]; and ultimate disposal by nuclear transmutation of the long-lived nuclides to short-lived species [*Gregory and Steinberg*, 1967; *Claiborne*, 1972; *Platt and Ramsey*, 1973; *Kubo and Rose*, 1973]. Continental media or methods mentioned in the literature as possible future HLW repositories include the following: bedded salt and salt domes [*National Academy of Sciences–National Research Council*, 1970; *Gera and Jacobs*, 1972; *Blomeke et al.*, 1973]; brine aquifers [*National Academy of Sciences–National Research Council*, 1957, 1966]; thick shale or clay sequences [*Gera and Jacobs*, 1972; *Ferro et al.*, 1973]; tunnels or dry mines in granite or desert hills [*National Academy of Sciences–National Research Council*, 1957, 1966]; unsaturated zones in desert environments [*National Academy of Sciences–National Research Council*, 1966]; river deltas [*Zeller and Saunders*, 1972]; ice caps [*Zeller et al.*, 1973]; surface storage in thick, air- or water-cooled vaults [*Szulinski et al.*, 1973]; incorporation in artificial silicate melts generated within nuclear chimneys [*Cohen et al.*, 1971]; and desert pyramids [*Starr and Hammond*, 1972]. Research emphasis in the past decade has gone principally toward perfecting several methods for solidification of the liquid wastes [*Schneider*, 1971; *Mendel and McElroy*, 1972; *Isaacson and Brownell*, 1973] and for detailed evaluation of bedded salt [*Bradshaw and McLain*, 1971; *Blomeke et al.*, 1973] as the preferred geologic medium for their disposal. The suitability of the other cited geologic media for HLW storage has yet to be studied in detail.

The purpose of this paper is to evaluate, in general terms, very thick (100–600 m) unsaturated zones found locally in the Southwest as potential repositories for HLW. The unsaturated zone, also commonly referred to as the vadose zone or zone of aeration, comprises the consolidated or unconsolidated rocks between the land surface and the water table. Rocks within the unsaturated zone contain interstitial water (termed hereafter vadose water) held tightly by capillary and molecular forces. This water may range from a few percent of the pore volume in relatively porous and permeable rocks, such as sand, gravel, and clean sandstone, to as much as 90% of pore volume in porous but poorly permeable rocks, such as clay, shale, clayey siltstone, and zeolitized ash-fall tuff. The water content of a given rock in the unsaturated zone at a given time is a function not only of physical properties of the medium but also of depth of burial, permeability of overlying and underlying strata, and climate. The unsaturated zone is currently being used for the disposal and storage of liquid and (or) solid low- and intermediate-level wastes at Hanford, Washington; Idaho Falls, Idaho; and other places. Use of these zones as a repository for the storage of solidified HLW has received only parenthetical mention in the literature [*National Academy of Sciences–National Research Council*, 1966; *Merrit*, 1967; *Richardson*, 1962], and the potential of very thick unsaturated zones as repositories has received no discussion.

Before proceeding, the author wishes to acknowledge that certain of his colleagues believe that this paper appears to advocate a single and preferred method of HLW storage. This is not the author's intent. However, storage in thick unsaturated zones in arid regions may be a potential alternative or supplement to other methods, and accordingly it merits preliminary evaluation and possible further research. Indeed, the need for detailed study of alternate methods of HLW storage and disposal has been stressed by *Kubo and Rose* [1973] in their recent overview of the nuclear waste situation.

Unsaturated Zone Storage

Unsaturated zones 100 m thick are common in the Southwest beneath the upper reaches of piedmont alluvial plains, and zones 100 to 600 m thick occur beneath mesas and plateaus and even beneath some valley floors, specifically valleys within the interbasin groundwater flow province of eastern Nevada [*Winograd*, 1961; *Winograd and Thordarson*, 1974; *Eakin*, 1966]. The great depth to water table in these areas is due to a combination of one or more factors, including moderate to high relief, aridity, relatively permeable rocks within the unsaturated zone, and regional aquifers with topographically low outlets. Solidified HLW from fuel reprocessing plants might be emplaced in such thick unsaturated zones in at least three ways: (1) placed at the bottom of shallow (30–40 meter) drill holes and backfilled to the surface; (2) buried in deep trenches; or (3) buried in the floor or walls of tunnels driven into the sides of mesas or plateaus. Placement within shallow drill holes would appear to minimize both cost and disruption of the landscape, and this mode of storage, illustrated in Figure 1, is assumed hereafter. It is also assumed that the HLW will be in the form of a glass product of relatively low solubility.

(The leachability of glassy and microcrystalline HLW solids of various compositions produced for the USAEC in pilot plants ranges from 10^{-1} to 10^{-7} g/cm^2-day [*Schneider*, 1971; *Mendel and McElroy*, 1972]. *Merrit* [1967] reported a leachability as low as 10^{-10} g/cm^2-day for HLW in a nepheline syenite glass. For comparative purposes, the leachability of common household Pyrex glass is about 5×10^{-7} g/cm^2 day. The leachabilities reported are to distilled water at 25°C and would probably be one or more orders of magnitude greater at temperatures present at the surface of buried waste canisters. In addition, devitrification of some glasses results in an increase in leachability of several orders of magnitude [*Mendel and McElroy*, 1972]. Considerably more laboratory work appears mandatory for predictions of the change in leachability of glassy solids left in the unsaturated or saturated zones for even relatively short periods of 10–100 yr.)

Emplacement by any of the cited methods is tentatively considered to be storage, because it offers the possiblity of retrieval in the event of a design miscalculation or development of a superior storage or disposal scheme. Disposal in salt, by contrast, is for practical purposes generally considered to be irretrievable [*Gera and Jacobs*, 1972, p. 17], as is disposal by means of most of the deep disposal methods listed above.

An evaluation of the unsaturated zone as a medium suitable for long-

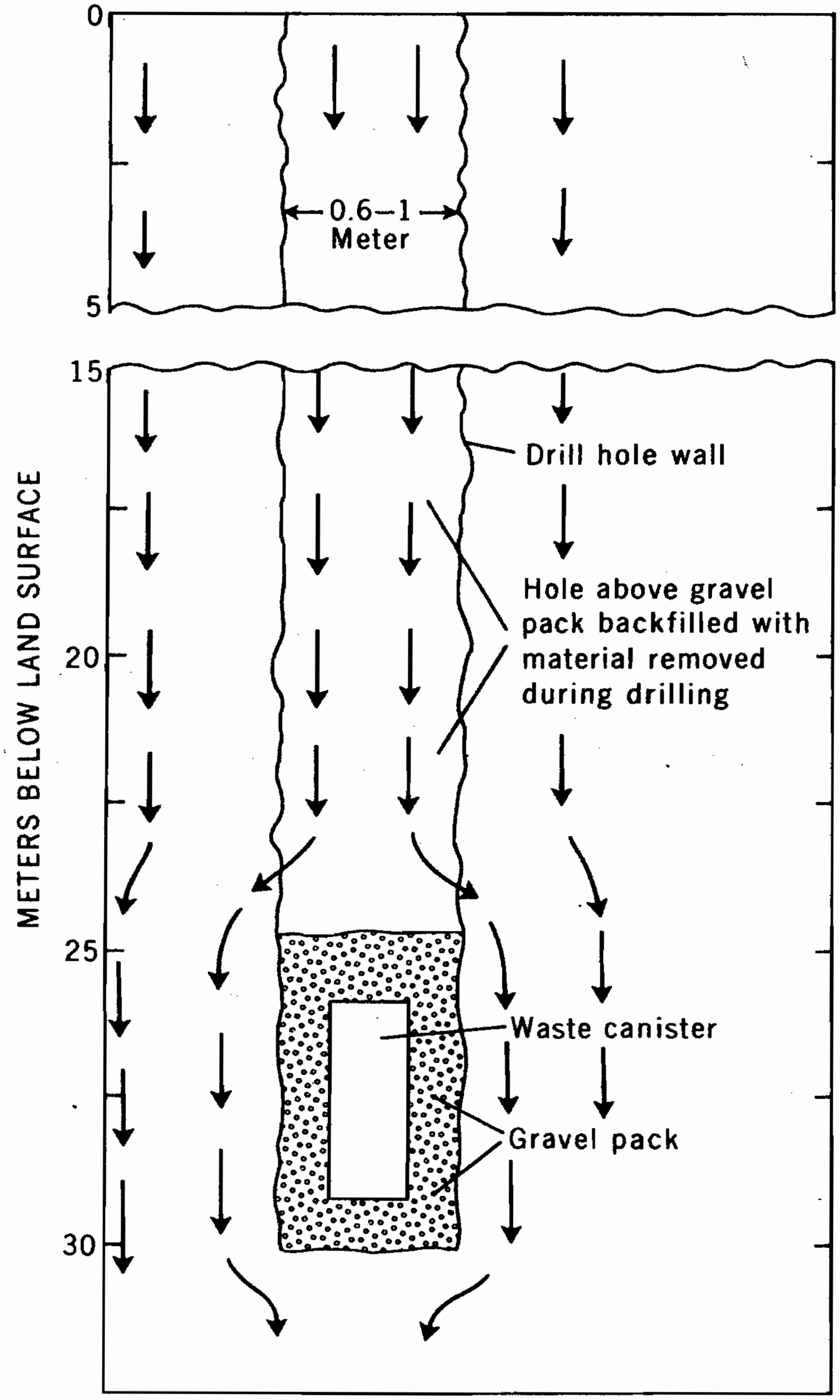

Fig. 1. Diagrammatic representation of storage of solidified high-level wastes at bottom of hole drilled 30 m into the unsaturated zone and pattern of movement of deep infiltration. Arrows indicate movement of the vadose water around, rather than into, the gravel pack owing to the higher interfacial tension of the fluid in the finer-grained host rock than in the gravel.

term storage of HLW must consider (1) the likelihood that the wastes will be dissolved and carried to the water table during present or pluvial climates; (2) the likelihood of the wastes being inundated by a rising water table, or the surface of the storage field being inundated by a lake during return of pluvial climate; (3) the degree to which the wastes are protected from exhumation by erosion during the next 10^3 to 5×10^5 yr; (4) the effects of a strong heat source upon vapor and water movement in the unsaturated zone, upon the waste canisters, and upon density of plant life at the surface; and (5) logistical and economic considerations vis-à-vis other proposed storage schemes. Such an evaluation requires a synthesis of pertinent data and notions from many fields, of which hydrogeology, paleoclimatology, geomorphology, pedology, physics of unsaturated flow, ion exchange and glass chemistry, physics of heat flow, radioactive waste disposal technology, and public relations are the most important.

Hydrogeologic, geomorphic, and paleoclimatic controls on unsaturated-zone storage are stressed in this paper; other equally important aspects of such storage are only outlined or omitted. Thus the synthesis is incomplete. Moreover, hydrogeologic data for the unsaturated zone are meager. Accordingly, the evaluation should be considered only as an overview of the potential assets and liabilities of thick unsaturated zones as HLW repositories. Despite its admittedly preliminary nature, the evaluation presented is believed to be timely in view of recent recommendations for study of new HLW handling schemes [U.S. Atomic Energy Commission, Press Release P-143, May 18, 1972; *Kubo and Rose*, 1973].

Assets of Unsaturated-Zone Storage

Hydrogeologic and logistical factors seemingly favorable to the utilization of thick unsaturated zones of the Southwest as repositories for HLW storage include (1) the probable absence of an effective mechanism to dissolve and transport the radionuclides to a deep water table under present climatic conditions, (2) probable protection from exhumation by erosion in a time frame of several thousands of years, (3) availability of remote federally owned lands with suitable unsaturated zones, and (4) relative ease of placement and retrieval. These are examined below.

Hydrologic, geomorphic, and pedologic evidence suggest that little or no recharge (namely, infiltration of precipitation to the water table) occurs beneath interfluves (interstream areas) in the arid and semiarid portions of the Southwest under present climatic conditions. (Pluvial conditions are discussed below.) In many places in the Southwest, evaporation from free water or class A-pan surfaces exceeds precipitation by 4 to as much as 20 times [*Environmental Sciences Services Administration*, 1968]. Although this in itself does not rule out periodic recharge by seepage along major arroyo bottoms, deep infiltration beneath closed depressions (such as abound in the southern High Plains), or precipitation directly entering outcrops of aquifers in mountainous areas, it does suggest that deep infiltration, leading to recharge on interfluves within the arid zone, is in general very small, if it occurs at all. A few studies of soil moisture content and moisture budgets for the semiarid zone soils support this notion [*Arkley*, 1963; *Aronovici and Schneider*, 1972; *Abrahams et al.*, 1961; I. Remson, personal communication, 1972]. However, to prove or disprove the occurrence of any recharge from precipitation falling on arid or semiarid zone interfluves at any given site would require measurement of ambient soil moisture and one or more potentials (matric, gravitational, osmotic, and pneumatic) affecting unsaturated flow.

To my knowledge, such field measurements have seldom been attempted for depths below those of interest to agronomists, usually up to 200 cm. However, where detailed studies have been made, there is a strong indication that recharge events are not common. Detailed studies by *Freeze and Banner* [1970] on the semiarid prairies of Saskatchewan using tensiometers, neutron meters, and piezometers indicate that relatively intense rains (about 10 cm/2 days) may or may not cause infiltration to the water table dependent upon depth to water table, antecedent soil moisture conditions, and position in the regional groundwater flow system. Potential evapotranspiration on the Saskatchewan plains is only 30% greater than annual precipitation, which is about 41 cm, and water table depths in the study area varied from 1 to 4 m. *Isaacson et al.* [1974] measured variations in tritium, water potential, and temperature in the unsaturated zone to depths of up to 92 m (the water table) at Hanford, Washington. Their work indicates that the fraction of annual precipitation (16 cm) that infiltrates to depths of up to 7 m during the wet winter months is removed by evaporation and evapotranspiration during the summer.

The formation of widespread pedogenic caliche in the arid and semiarid zones of the world also strongly suggests that precipitation only penetrates a few feet into the ground in such regions prior to evaporation and deposition of $CaCO_3$ [*Arkley*, 1963; *Brown*, 1956; *Reeves*, 1970; *Flach et al.*, 1969; *Gile et al.*, 1966; *Gardner*, 1972]. Evidence that moisture from precipitation or streamflow never penetrated below the root zone in certain widespread alluvial-fan deposits, even during times of glacial and lacustrine expansion during the Pleistocene in central California, is presented by *Bull* [1972].

The above cited studies, involving several independent lines of evidence, suggest that in much of the Southwest, infiltration of precipitation on interfluves rarely reaches water tables of even intermediate depth (10–100 m). Admittedly, the studies cited are few, and the degree to which their conclusions are transferable to conditions at a specific storage site will depend on the degree of similarity in hydrogeologic, geomorphic, pedologic, and climatic conditions.

Granting that recharge to interfluves appears to be rare under present climatic conditions, periodic deep infiltration—perhaps following the successive occurrence of several low-intensity, long-duration rainfall events, the shift of a major arroyo over a part of the storage field, or the movement of infiltration by means of fractures in the soil zone or bedrock—cannot be ruled out. Contact of such infiltrating water with the waste canisters should in principle be preventable if the canisters are surrounded by a well-sorted gravel pack that is considerably coarser than the host rock at depth of burial (Figure 1).

The role of the gravel pack is as follows. In contrast to saturated flow, wherein water in fine-grained sediments can move into adjacent coarser and more permeable strata, in unsaturated flow the reverse occurs. Water is drawn more strongly into the finer than into the coarser sediment. It has been demonstrated both in the laboratory and in the field that nearly saturated fine-grained sediments can overlie or even surround dry coarse sands or gravel lenses [*Corey and Horton*, 1969; *Horton and Hawkins*, 1965; *Miller*, 1969; *Palmquist and Johnson*, 1962, also unpublished data, 1960; *Rancon*, 1972; *Stuart and Dixon*, 1973]. No water will enter the coarser sediment until the finer-grained sediment is nearly or completely saturated. More correctly, drainage into the unsaturated coarser stratum would begin at the saturation level at which gravitational forces exceed interfacial tensional forces. In fine-grained sediments adjacent to well-sorted gravel, this saturation level may approach complete saturation before drainage occurs. Differences in moisture tension (also called matric potential) are responsible for this behavior. By placing the waste canister in a well-sorted gravel that is much coarser than the adjacent natural material, the higher moisture tension in the finer material should prevent contact of vadose water (in the event of deep infiltration) with the canister until such times as the surrounding stratum is nearly saturated.

If vadose water should still somehow periodically contact and dissolve radionuclides—for example, in the absence of a gravel pack and following corrosion of the steel canisters and unusually deep infiltration—two other major buffers would retard movement of dissolved nuclides to deep water tables. Sorption processes, including ion exchange, constitute the first buffer. Admittedly, the effectiveness of such a buffer is a function of numerous variables and will be difficult to evaluate quantitatively. Moreover, because of the partitioning of dissolved nuclides between mineral phases and vadose water, some fraction of the dissolved nuclides will reside in the vadose water should such water ever reach the water table. Yet the surface area available for sorption in granular rocks comprising an unsaturated zone several hundred to possibly as much as 600 m thick is enormous.

The thickness, and stratification of the unsaturated rocks potentially constitute a second major buffer to the movement of a wetting front from the waste canisters to the water table. Differences in bulk capillarity between strata comprising the unsaturated zone would favor horizontal and retard vertical distribution of vadose water for the same reasons outlined in the discussion of the role of the gravel pack.

The possibility of exhumation of buried HLW by erosion in the next 10^3 to 5×10^5 years has to be considered thoroughly. *Schumm* [1963] reports average denudation rates for arid and semiarid terrane of 9–18 cm/1000 yr for drainage basins 80–4000 km^2 in area. Considerably higher rates occur in rugged mountainous terrain and badlands, but undoubtedly much lower rates exist on mesa and plateau surfaces owing to cap rock hardness and low relief length ratios. Using the cited average values, the time needed to remove 20 m of overburden would vary from about 100,000 to 200,000 yr. Slope retreat rates have been variously estimated as 0.1 to 4 m/1000 yr [*Melton,* 1965; *Schumm and Chorley,* 1964; *Carson and Kirby,* 1972; *Purtymun and Kennedy,* 1971; W. B. Bull, personal communication, 1972], with values under 2 m/1000 yr more probable; thus waste canisters buried 1000 m from the edge of a scarp should not be exhumed by slope retreat in the next 500,000 yr, granting tectonic stability.

Thus it is probable that unsaturated-zone burial sites can be found that will protect HLW from exhumation for a period of 1000 yr, a time adequate to permit the decay of ^{90}Sr and ^{137}Cs, which constitute 99% of the long-lived nuclides in fuel-reprocessing wastes, and most likely for a period of several tens of thousands of years. The probability for containment for periods of sufficient length to permit decay of all the transuranic elements, namely periods of several hundred thousand years, is small, and an estimate of this probability, if one could be made, would require detailed evaluation of the tectonic as well as the geomorphic history of target areas.

Use of denudation rates in a safety analysis of a burial site is on the one hand a conservative approach in that it emphasizes principally erosional processes. Work by *Gile* [1970], *Hawley and Kottlowski* [1969], and *Ruhe* [1967] and studies of caliche genesis cited earlier suggest that depositional processes are also at work tending to stabilize certain geomorphic surfaces of the Southwest, for example, the aggradational processes responsible for many caliche deposits. Therefore a synthesis of both denudation (including scarp retreat) and aggradational rates would give a more realistic picture of the stability of a given geomorphic surface. On the other hand, use of measured erosion rates to determine the extent of denudation during a time frame of 10^4 to 5×10^5 yr is very risky because of the potential marked effects of uplift (by folding or faulting), or subsidence, on erosion rates. Some uncertainties present in determination of present erosion rates have been summarized by *Wilson* [1973].

The problem of predicting denudation and scarp retreat rates might be largely avoided in the short term (10^3–10^4 yr) by consideration of burial sites beneath aggrading portions of piedmont alluvial plains within topographically closed basins. As mentioned previously, water table depths beneath certain such valleys in the Southwest, particularly in eastern Nevada, range up to 600 m below land surface [*Winograd and Thordarson,* 1974; *Eakin,* 1966]. Valley sites chosen would, however, have to be located higher on the piedmont alluvial plains than the spill point of possible pluvial lakes (see below).

In summary, the principal factors seemingly providing isolation of solidified HLW buried in thick unsaturated zones from the hydrosphere or biosphere include (1) paucity of deep infiltration leading to groundwater recharge under present climatic conditions, (2) presence of a gravel pack around the waste canisters to prevent contact of vadose water with the solid wastes, (3) sorption processes, particularly when considered in light of rarity of elution events and large thickness of the unsaturated zone, and (4) certain protection from erosion for a period of 1000 yr and likely protection for a period of several tens of thousands of years. The above conclusions were arrived at principally on the basis of literature review. The degree to which they apply to rocks comprising the unsaturated zone at a specific site in the Southwest can, of course, only be determined by detailed study.

A major consideration in selection of a HLW repository is public reaction to the proposed storage or disposal. Areas remote from major population centers and not supporting viable farm, ranch, or mining economies are likely, other safety considerations being equal, to be more readily acceptable to the public as HLW repositories than areas not having such characteristics. Vast tracts of federally owned land in the Southwest have been closed to the public for two to three decades owing to their use as bombing and gunnery ranges, rocket development and test ranges, or nuclear test sites. Portions of these tracts contain extensive thick unsaturated zones and constitute attractive targets for HLW storage. The Nevada Test Site in southern Nevada, used for two decades for testing of nuclear weapons, is an example of an area that might be acceptable to the public by virtue of this prior history. Large mesas or plateaus are absent within the Nevada Test Site, but thick (150–600 m) unsaturated zones occur beneath the valley floors [*Winograd and Thordarson,* 1974]. In addition, a thick (50–300 m) aquitard (stratum of very low permeability), composed principally of clay and zeolite minerals, separates the unsaturated zone from the principal regional aquifer of the area [*Winograd and Thordarson,* 1974], thus providing an additional measure of safety against groundwater contamination in the event of deep infiltration. Logistically, this test site appears suited for receipt of solidified HLW from fuel-reprocessing plants built in the Southwest or Northwest. A main branch of the Union Pacific Railroad runs through Las Vegas, Nevada, 97 km (60 mi) from the site, and a four-lane highway connects the city to the site.

A final possible logistical and safety asset of shallow storage in the unsaturated zone involves relative ease of emplacement or retrieval of the HLW if such a course of action should become necessary, for example, in the event of a design miscalculation or the development of a superior storage or disposal scheme. Drilling of 1 m (or larger) diameter emplacement holes can readily be accomplished with modern large-diameter hole-drilling equipment, as can the task of placing a gravel pack. Retrieval, if needed, will be more difficult but might be accomplished by reaming the hole to the top of the canister and then retrieving the canister and gravel pack simultaneously by means of a specially designed core barrel.

Complications exist, of course. First, the lifetime of the steel canisters placed at depths of 30–40 m in an unsaturated zone is unknown. Although the canisters will be buried at depths below significant seasonal variations in moisture content and temperature, the effects of several hundred degree Celsius heat flux on the integrity of the canisters in this environment is unknown; the canisters could disintegrate in a few decades.

Second, it is estimated that by the year 2010, 75,000 HLW canisters (each 3 m long and 30 cm in diameter) will need burial [*Blomeke and Nichols*, 1973]. If these canisters were to be buried 1 to a hole and the holes were drilled on 30-m centers, an area of about 8 X 8 km would be needed; if they were drilled on 15-m centers, an area of about 4 X 4 km would be needed. The capacity of a given area might be doubled or tripled, however, by placing 2 or 3 canisters per hole at depths determined by heat dissipation considerations. In any event, drilling of such large numbers of holes, with concomitant disruption of the surface, might measurably increase both erosion and infiltration rates at the site.

Third, after placement of a few thousand canisters, it may be argued that a distinction between storage and disposal is misleading, because even granting accessibility, it is improbable that the canisters would ever be removed. These caveats notwithstanding, the advantage of shallow emplacement vis-à-vis deep disposal is simply that during the first few decades of HLW handling—a time in which, presumably, considerable experience will be gained—the proximity of the wastes to the surface would facilitate excavation if such a step should become necessary for whatever reason.

Liabilities of Unsaturated Zone Storage

Potentially serious liabilities of unsaturated zone storage include (1) the necessity and difficulty of guaranteeing that the wastes will not be exhumed by erosion during the next several hundred thousands of years, the time needed to permit decay of the longer-lived transuranic elements (namely, $^{238-240}Pu$, ^{241}Am, and ^{243}Am); (2) the necessity and difficulty of predicting the effects of a return of pluvial climate upon the proposed storage scheme; (3) the complexity of processes in, and difficulty of in situ measurements of unsaturated flow parameters for, an unsaturated stratified medium; (4) evaluation of stresses created by the radiogenic heat both within and on the surface of the unsaturated zone; and (5) necessity of protecting the surface of the burial area. The first listed liability was discussed previously; the remaining ones are discussed below.

To evaluate isolation of the wastes from the hydrosphere and biosphere during a time frame of 10^3 to 5 X 10^5 years, or even during the next few hundred years, estimates must be made regarding changes in recharge rates, position of water table, and erosion rates if the climate should become much wetter than at present, namely, in the eventuality of a return to pluvial climatic conditions. Such estimates, given below, are based in part upon inferred climatic conditions in previous pluvial periods, but they offer no guarantee that the next pluvial will not be considerably wetter than previous ones [*Kukla and Matthews*, 1972].

(Although many Quaternary geologists expect the present interglacial epoch to end perhaps within the next few millennia or even centuries, the possibility that man's modification of climate may partly override such an occurrence cannot be ignored [*Budyko*, 1972]. For the purpose of this safety analysis, we assume that pluvial climatic conditions may reoccur in the Southwest during containment of the HLW.)

Geomorphic evidence for the existence of numerous lakes and paleobotanical evidence for the depression of vegetation zones 300–1000 m during the pluvial periods are well documented in the Southwest [*Mehringer*, 1965; *Mehringer and Ferguson*, 1969; *Van Devender and King*, 1971; *Wells*, 1966; *Wells and Berger*, 1967]. Whether these features principally reflect increased precipitation, decreased evaporation, or some combination of the two is under debate [*Leopold*, 1951; *Galloway*, 1970; *Reeves*, 1966, 1973; *Snyder and Langbein*, 1962]. Regardless of the outcome of this debate, the available paleoecological and pedologic evidence suggests that areas of low and intermediate altitudes in much of the Southwest—excluding major uplands such as the Colorado Plateau and portions of the northern Great Basin—probably were still partly semiarid during the pluvials. Paleobotanical evidence for the Mohave Desert suggests that areas below about 800 m altitude were still partly semiarid during the last pluvial (P.J. Mehringer, Jr., personal communication, 1972). Pedological, hydrological, and paleontological evidence suggests the possibility of semiarid conditions at altitudes as high as 1300 to perhaps 1900 m in the northern Great Basin of Nevada and in central New Mexico [*Birkeland*, 1969; *Snyder and Langbein*, 1962; *Harris and Findley*, 1964]. In west Texas, by contrast, subhumid conditions may have existed [*Reeves*, 1973]. It is probable that during the pluvials, as today, climate in the Basin and Range province varied not only with latitude and altitude but also with longitude (reflecting proximity to the Sierra Nevada rain shadow).

If detailed studies conclude that unsaturated-zone storage is acceptable under present climatic conditions, it may also be adequate under pluvial conditions, provided that future pluvials are not considerably wetter than past ones and provided that precautions are taken in site selection. For example, sites on lower portions of valley floors within topographically closed basins would be avoided regardless of the present depth to water table or aridity lest the storage site be flooded by a future pluvial lake. Similarly, given two mesas with identical depths to water table but with a 1000-m difference in cap rock altitude, the lower mesa (presumably receiving less precipitation) would be a preferred choice to assure a dryer storage environment during return to pluvial conditions.

Regarding possible inundation of buried wastes by a rising water table during pluvial times, the following general comments are in order. Undoubtedly, the water table fluctuated during the Pleistocene in response to climatic changes. However, the magnitude of water table rise beneath a mesa or valley floor is a function not only of recharge amounts but also of (1) hydrogeologic boundary conditions, principally relief; (2) distribution of permeability and porosity within the flow system; and (3) position within the flow system. In semiarid areas with moderate relief, perhaps 150–600 m, the three listed factors often completely overshadow climate as a control on depth to water. This is clearly seen in some of the valleys of eastern Nevada where water table depths vary from 30 to as much as 600 m beneath adjacent valleys [*Winograd and Thordarson*, 1968] receiving comparable precipitation. Even in humid climates, deep water tables are common in terrane combining relief with rocks of moderate permeability (within the unsaturated zone). Accordingly, the likelihood that solidified HLW buried at shallow depths beneath carefully selected mesas, plateaus, or valleys will be inundated by a rising water table appears remote even if the climate of a future pluvial time should approach subhumid conditions.

Even in the presence of subhumid pluvial climate, several factors previously discussed would certainly retard, and possibly prevent, the dissolution and transport of radionuclides to the water table. These factors are (1) the gravel pack surrounding the waste canisters, (2) sorption processes, (3) the great depth to water table, and (4) the affect of stratification on retarding vertical flow in an unsaturated environment. (Admittedly, stratification might also lead to creation of perched zones of saturation.)

Schumm's [1963] data on denudation rates of modern drainage basins receiving different amounts of precipitation offer some insight to expectable changes in erosion rates during a pluvial period. His data suggest that erosion rates in semiarid areas are somewhat higher than rates in the arid zone and considerably higher than rates in humid terrane. The range of average denudation rates cited and utilized previously, namely, 9–18 cm/1000 yr, included the highest rates reported by Schumm for any climatic setting. These rates should therefore also be representative of possible pluvial erosion rates.

The complexity of unsaturated flow processes in porous media, the difficulty of in situ measurement of parameters characterizing these processes (particularly at depths in excess of a few meters), and the common heterogeneity of sedimentary rock constitute another major liability to use of the unsaturated zone. Unsaturated moisture flow is governed not only by the well-known capillary (or matric) and gravitational potentials, but also by osmotic and pneumatic potentials [*Nielsen et al.*, 1972]. These potentials are complex functions of three-dimensional variations of water content, gas content, grain shape and size distributions, water chemistry, mineralogy, and temperature. Measurement of these potentials is extremely difficult, particularly when pore water content is a fraction of pore volume, the probable case in thick unsaturated zones of the Southwest. Interpretation of measurements may be further complicated by coupling of the potentials. Moreover, the sedimentary rocks comprising the unsaturated zone are layered and often heterogeneous, even within a single stratum. In a word, prediction and field measurement of vadose water flow through even the upper few tens of meters of a thick unsaturated zone will be extremely difficult, and the transference value of detailed studies at a site will be limited. Yet a predictive capability is needed in order to evaluate the effects of possible stresses induced in the unsaturated zone by the placement of a major heat source. We turn next to an outline of such possible stresses.

Analyses of possible adverse (or favorable) stresses induced by radiogenic heat from HLW will probably be one of the most difficult, time-consuming, and costly parts of a detailed evaluation of unsaturated-zone storage. Factors that appear paramount and differ in type from heat flow related problems of disposal in bedded salt include the following:

1. The thermal conductivity of rocks that make up the unsaturated zone varies widely and is considerably less than salt. The thermal conductivity of porous media within the unsaturated zone may range from 0.5×10^{-3} cal/cm sec °C for dry alluvium to 6×10^{-3} cal/cm sec °C for dry sandstone; these values are about 1/30 to 1/2 that of rock salt with an average conductivity of about 14.5×10^{-3} cal/cm sec °C [*Clark*, 1966]. The lower conductivity of rocks commonly found in the unsaturated zone will undoubtedly necessitate longer surface storage of the HLW prior to emplacement, smaller canisters, or wider space between waste canisters than would disposal in bedded salt.

2. Difficulty of predicting the effects of heat transfer in media in which, unlike bedded salt, there is convection as well as conduction. Related problems include determination of the region in which there may be condensation of water vaporized in the vicinity of the canisters, possible creation of a gas drive and the significance of such a drive in moving moisture in the unsaturated zone, and effects of dry and wet steam (if any) on the canisters and glassy solids containing the HLW.

3. Magnitude of dehydration effects in fine-grained strata through loss of water of crystallization. Magnitude of the attendant volume change and cracking if dehydration occurs.

4. Effect of heat on density of surface vegetation and subsequently on rates of denudation by means of deflation as well as by surface runoff.

Despite the above outlined caveats, the influences of intense heat flow need not necessarily be detrimental to unsaturated-zone storage. It is possible, for example, that the net effect of the heat will be to significantly increase evaporation from the upper several meters of unsaturated zone, thereby precluding any deep infiltration. Similarly, unsaturated moisture flow should be away from the canisters. In any event, to the extent that such heat ill keep moisture from the canisers, its effectiveness will decrease with the decay of ^{90}Sr and ^{137}Cs, which constitute 99% of the initial curie content of HLW but which produce 90% of their total heat within about 100 yr.

In summary, the principal technical liabilities of unsaturated-zone storage appear to be two: (1) the possibility of exhumation of the wastes by erosion prior to decay of all the transuranic elements to safe levels and (2) the considerable research effort that appears mandatory to evaluate response of the unsaturated zone to emplacement of a major heat source. The other listed potential liabilities appear negligible by comparison.

Unsaturated Zone Storage Versus Surficial Storage and Deep Disposal

Storage of HLW at relatively shallow depths in thick unsaturated zones—if not precluded by heat dissipation and other constraints outlined above—appears to have some advantages vis-à-vis surficial storage in air- or water-cooled concrete vaults, on the one hand, and deep disposal in bedded salt or other geologic media on the other hand.

The principal asset of unsaturated zone storage vis-à-vis surface storage in concrete vaults is the absence of a need for intense surveillance to guard against vandalism, sabotage, theft, or the blundering of unaware descendants. Some surveillance of an unsaturated-zone burial site undoubtedly would be necessary, but it would be nominal by comparison with surface storage. Care would have to be taken, for example, to prevent intentional ponding of water, deep excavation, drilling, and irrigation by our descendants for up to a thousand years (see below). But the aridity, great depth to water table, and topography (in the case of mesas and plateaus) would in themselves discourage such activities even in the absence of surveillance. Surprisingly, the necessity for surveillance applies even to deep disposal in bedded salt [*Weinberg*, 1972]. The utilization of nuclear energy assumes a high degree of social responsibility for centuries to millenia regardless of storage or disposal method used.

(Disposal of HLW in bedded salt is often described as providing isolation of such wastes into perpetuity without need for surveillance. However, when one talks of isolation of HLW for periods of several hundred thousands of years, it is clear that some surveillance is mandatory. For example, nominal surveillance of the surface over the bedded salt used will always be needed to prevent accidental drilling into the HLW [*Weinberg*, 1972]. Similarly, protection against flooding of the shaft by surface waters or by groundwater leakage from overlying aquifers [in event of deterioration or cracking of the grout separating these aquifers from the shaft] will also be required until such time as each shaft is backfilled to the surface.)

The principal assets of shallow storage in the unsaturated zone vis-à-vis deep disposal in bedded salt or other geologic media are twofold: (1) relative ease of retrievability and (2) placement up to 600 m above rather than below the water table. The proximity of the waste canisters to the surface (30–40 m) offers the possiblity of relatively easy monitoring and retrieval in the event of a major design miscalculation or of the development of a superior storage or disposal scheme. Retrievability from bedded salt, by contrast, would be extremely difficult owing to the limited life (6 months to a few years) of steel canisters placed in salt [*Gera and Jacobs*, 1972, p. 17]. (As was mentioned previously, the expectable lifetime of steel canisters placed in the unsaturated zone is not known. Regardless of canister lifetime, however, proximity of the wastes to the surface would facilitate excavation and removal should such a step ever become necessary.)

Gera and Jacobs [1972, p. 17] state: 'Disposal in salt should really be considered as ultimate. If the waste management scheme must include retrievability as a necessary condition, some alternative to salt disposal should be investigated.'

Disposal in nuclear cavities [*Cohen et al.* 1971] is also irretrievable, as is ice cap disposal [*Zeller et al.*, 1973].

Placement of solidified HLW hundreds to perhaps as much as 600 m above the water table in an arid to semiarid environment appears to offer an important safety advantage—in the event of a major design miscalculation, accident, or earthquake—over deep disposal in bedded salt or other media underlying freshwater aquifers. It is true that salt is easy to mine, is plastic (namely, self-sealing if fractured), and by its very existence indicates the absence of circulating ground waters in the geologic past. But, as was pointed out by *Kubo and Rose* [1973, p. 1207], '... these advantages are two-sided, for the very fragility (vulnerability to water) of the geologic structure is used as an argument in its favor, and the demonstrated stability refers only to past time, and not to the future, when conditions will likely be different. We may mistake an indicator of past quality for a substantive future property.' They state further (p. 1207): 'The long-term safety of the project depends on preventing the intrusion of water into the salt beds by any means. This could occur by natural means such as erosion, failure of overlying or underlying shale beds, boundary dissolution, and by man-induced means such as well borings.'

As was suggested previously, great care will have to be taken to prevent possible flooding of the shaft (leading to the salt) by surface waters or by groundwater leaking through the grout curtain separating the shaft from the aquifers overlying the bedded salt. Disruption of the grout curtain by an earthquake prior to sealing of the shaft might, for example, result in rapid flooding of the repository. Prediction and control of groundwater entry and exit from a nuclear cavity, in which *Cohen et al.* [1971] propose to incorporate HLW in silicate rocks by self-boiling, appears unlikely and risky, because of (1) the fractures created by the nuclear detonation and (2) the difficulty of emplacement and sealing of postshot drill holes. By contrast, a design flaw, accident, or earthquake is unlikely to result in flooding of an unsaturated zone HLW repository by either ground or surface waters. Ponding of water would, of course, follow a major earthquake at an unsaturated-zone site owing to disruption of site topography, and fissures would permit contact of water with some canisters, but no massive dissolution of rock would occur, and open fissures would eventually be sealed by siltation, if not by man.

The major liability of unsaturated zone storage vis-à-vis deep disposal in bedded salt or other deep media is the possibility of exhumation of the wastes by erosion prior to decay of the transuranic elements to safe levels. Deep disposal clearly offers a much higher probability of containment of the HLW against exhumation for the necessary several hundred thousand year decay time. Removal of the transuranic elements from HLW is clearly mandatory prior to serious consideration of thick unsaturated zones as HLW repositories.

Separation of the transuranic elements from the fission products in HLW is now under study as a long-term waste management method [*Gregory and Steinberg*, 1967; *Claiborne*, 1972; *Platt and Ramsey*, 1973; *Kubo and Rose*, 1973]. The incentive for such removal was succinctly stated by *Kubo and Rose* [1973, p. 1208], '. . . removing the actinides [namely, the transuranic elements plus elements 89–92] turns a million-year problem into a 700-year one.' The separated transuranic elements would be (1) transmuted to short-lived species by recycling, a procedure considered to be economically feasible by *Kubo and Rose* [1973], or (2) disposed of extraterrestrially [*Platt and Ramsey*, 1973]. When and if chemical separation of the transuranic elements from the HLW becomes a reality, storage in the unsaturated zone would appear to be an attractive compromise between surface storage and deep disposal.

Conclusions

A comparison of the principal assets and liabilities of unsaturated zone storage is given in Table 1. Because of the several hundred thousand years needed for decay of the transuranic elements, the first two listed liabilities effectively preclude use of thick unsaturated zones as HLW repositories. Removal of the transuranic elements from HLW (and their disposal by recycling) might, on the other hand, make unsaturated-zone-storage an attractive compromise between surface storage in concrete vaults and deep disposal in bedded salt or other geologic media. Storage in thick unsaturated zones appears suitable for isolating the long-lived fission products ^{90}Sr and ^{137}Cs from the hydrosphere and biosphere for the 600–1000 yr needed for decay of these nuclides and in addition offers the possibility of relative ease of retrievability and only nominal surveillance. But considerable research is mandatory to define ambient movement and content of water and gases in common rocks comprising thick unsaturated zones of the Southwest and the response of these rocks to emplacement of a major heat source. Indeed, thick unsaturated zones beneath deserts of the world (some possibly overlying tectonically stable platform areas) constitute unused space with a potentially significant capacity to buffer the environment against degradation by a variety of solidified toxic as well as radioactive wastes. Yet to date, few quantitative hydrogeologic or geophysical studies have been made of these zones below a depth of a few meters.

TABLE 1. Comparison of Some Assets and Liabilities of Thick Unsaturated Zones as Repositories for Solidified High-Level Wastes

Assets	Liabilities
Exhumation of wastes by erosion unlikely in time frame of 10^3–10^4 years.	Potential for exhumation of wastes by erosion in time frame of 10^4 to 5×10^5 yr difficult to assess.
Transport of dissolved radionuclides to deep water tables unlikely under present climatic conditions.	Potential for transport of dissolved radionuclides to water table under pluvial climatic conditions difficult to assess.
Potential availability of remote federal lands with thick unsaturated zones.	Extensive field and laboratory studies needed to evaluate stresses caused by placement of major heat source in unsaturated zone.
Relative ease of placement and retrieval in event of design miscalculation or development of a superior storage or disposal system.	Nominal monitoring of surface of storage site mandatory.

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